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WGS 84 COORDINATE VALIDATION AND IMPROVEMENT FOR THE NIMA AND AIR FORCE GPS TRACKING STATIONS

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Using 10 days of Global Positioning System (GPS) pseudorange and carrier phase data collected in 1995 from 31 stations and 24 Block II/IIA satellites, estimates of GPS clocks, orbits, and tracking station coordinates were generated. The 31 sites consisted of the 12 National Imagery and Mapping Agency (NIMA) and Air Force operational stations, an additional NIMA site at Holloman Air Force Base, and 18 International GPS Service for Geodynamics (IGS) Rogue receiver sites. Ten of the NIMA and Air Force operational sites had their coordinates previously determined using GPS data. The results of this work suggest that the estimated 10 cm, one sigma, per component accuracy indicated for these 10 stations was conservative. The new World Geodetic System 1984 (WGS 84) coordinates generated for the 12 NIMA and Air Force operational stations are reported at the 1994.0 and 1997.0 epochs. The estimated accuracy of the new coordinates is better than 5 cm, one sigma, per component.

Orbits estimated using the new WGS 84 coordinates agree better with the IGS final combined orbits, derived in the International Earth Rotation Service Terrestrial Reference Frame 1994, than orbits estimated using the old coordinates. The overall rms orbit-URE of the new orbits is estimated to be 12 cm, an improvement of 2 cm rms over the old orbits. Systematic differences with respect to the IGS orbits have been significantly reduced.

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GPS, station coordinates, geodetic coordinates, WGS 84, ITRF94, DMA, NIMA, OCS, Air Force, IGS, IERS, satellite orbit, Ashtech, Rogue, TurboRogue

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FOREWORD

The first realization of the World Geodetic System 1984 (WGS 84) reference frame was made using Doppler data collected from TRANSIT satellites and station position accuracy was at the meter level. In a study published two years ago, more than an order of magnitude improvement in the accuracy of station positions was achieved using Global Positioning System (GPS) data. The WGS 84 station coordinates documented in this report are estimated to have an accuracy of a few centimeters. This work was funded by the National Imagery and Mapping Agency (NIMA) and was performed in the Space Systems Applications Branch, Space and Weapons Systems Analysis Division, Warfare Analysis and Systems Department.

The authors would like to thank NIMA personnel Ms. Lisa McCormick, Mr. Brian Hagan, and Mr. Tom Creel for supplying the GPS tracking data. The authors would also like to thank NIMA employees Mr. Frank Mueller and Mr. Rich Marlen for supplying various types of data and software.

This report has been reviewed by Mr. Everett R. Swift, NIMA Program Manager, Dr. Jeffrey N. Blanton, Head, Space Systems Applications Branch, and Mr. James L. Sloop, Head, Space and Weapons Systems Analysis Division.

Approved by:

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INTRODUCTION

The National Imagery and Mapping Agency (NIMA*) operates a worldwide network of seven Global Positioning System (GPS) satellite tracking stations. Data from these stations and the five GPS Operational Control System (OCS) stations operated by the Air Force are used routinely by NIMA to generate GPS clock and orbit estimates. The seven NIMA sites are located in Australia, Argentina, England, Bahrain, Ecuador, the U.S. Naval Observatory (USNO) in Washington D.C., and China. The five OCS sites are located in Colorado Springs, Ascension, Diego Garcia, Kwajalein, and Hawaii. The coordinates of five of the seven NIMA sites (USNO and China not included) and all five of the OCS sites were determined previously using GPS data. USNO and China were added to the NIMA network after the initial GPS-realized coordinates were developed. This report documents a study performed to validate the accuracy of the coordinates of the 10 stations and to accurately determine coordinates for USNO, China, and an additional NIMA site at Holloman Air Force Base (AFB), New Mexico. The OMNIS Multisatellite Filter/Smoother system of programs (Reference 1) was used to generate estimates of GPS clocks and orbits, tracking station coordinates, and other parameters.

TRACKING DATA SETS

Two data sets were used in this study (Table 1). The first data set was used to derive and initially evaluate the new World Geodetic System 1984 (WGS 84) (Reference 2) coordinates. The first set consisted of 10 days of GPS pseudorange and carrier phase data from 32 sites and 24 Block II/IIA satellites. The 32 sites consisted of the 13 NIMA and Air Force stations and 19 International GPS Service for Geodynamics (IGS) Rogue receiver sites (Figure 1). As described later, only data from 31 of the 32 sites were useable for deriving high accuracy station coordinates. The 10 days of data began on December 5 (day number 339), 1995. The second data set used for further evaluation of the new coordinates consisted of nine days of GPS pseudorange and carrier phase data from the 12 operational NIMA and Air Force stations and 24 Block II/IIA satellites. The nine days of data, representing a span typically used by NIMA in their weekly production of GPS clock and orbit estimates, began on June 8 (day number 160), 1996. The second data set is the same as used by NIMA in production of the estimates for GPS week 857.

*The Defense Mapping Agency became part of the new National Imagery and Mapping Agency on 1 October 1996.

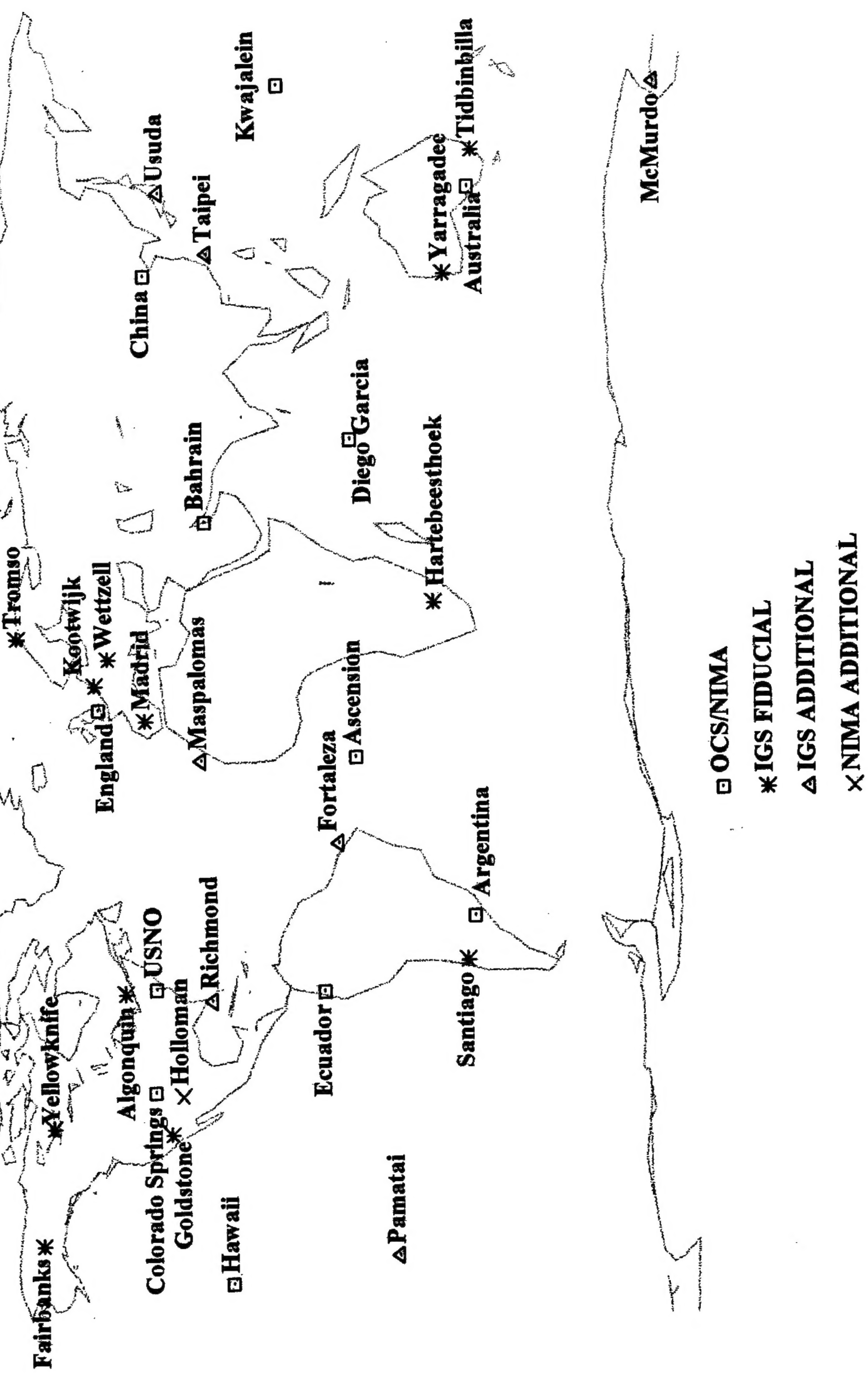

FIGURE 1. WORLDWIDE DISTRIBUTION OF TRACKING STATIONS

TABLE 1. DATA SET DESCRIPTIONS

Set	Span Day Nos., Yr.	No. of OCS/NIMA Sites	No. of IGS Sites	Comments
1	339 thru 348, 1995	13	19*	Used to derive coordinates and make initial evaluation.
2	160 thru 168, 1996	12	0	Used to further evaluate coordinates. Used by NIMA for GPS Week 857.

*Only 18 of the 19 IGS stations (Hartebeesthoek excluded) were used to derive the new WGS 84 station coordinates.

NIMA AND AIR FORCE DATA

Data from the seven NIMA and five Air Force operational sites consisted of 15-min smoothed pseudorange and carrier phase data. At all the NIMA sites except for China, a 12-channel Ashtech ZY-12 receiver was used to track all satellites in view. The Ashtech ZY-12 is a keyed receiver capable of tracking the encrypted pseudoranges broadcast by satellites in Anti-Spoofing (AS) mode. Deployed at China is an Ashtech Z-12 receiver, an unkeyed 12-channel receiver that tracks the AS-encrypted pseudoranges in a codeless mode (Reference 3). All the GPS satellites except PRN28 were operating in AS mode. Each Air Force site tracked all satellites in view using Stanford Telecommunications, Inc. receivers. Cesium frequency standards were used for both the NIMA and Air Force receivers. The GPS-realized WGS 84 station coordinates (Reference 4) were used for all the OCS/NIMA stations, except for the NIMA sites in Australia, England, USNO, and China. The antennas in Australia and England were moved subsequent to the station coordinate development. The WGS 84 coordinates of Australia and England were determined by GPS relative positioning, using the original position of the antenna as the reference site. The relative coordinates have an accuracy comparable to that of the original coordinates, estimated to be 10 cm per component (one sigma) (Reference 4). Sites at USNO and China were added to the NIMA network in 1995. The WGS 84 coordinates for these two sites were developed by NIMA using three days of GPS tracking data and their point positioning program (Reference 5). All OCS/NIMA station coordinates had a plate motion model epoch of 1994.0.

Selective Availability (SA) was also on during both data spans. The SA effect was removed from both the pseudorange and the carrier phase observations collected at the OCS and NIMA stations. Range differences were obtained by differencing consecutive carrier phase observations. Both pseudorange and range differences were processed through the OMNIS system of programs. Corrections were made to the data for transmission time effects, GPS antenna offset effects, solid Earth tide effects on station coordinates, relativity effects, tropospheric refraction effects, and plate motion effects on station coordinates. The GPS antenna offsets used are given in Table 2. Weather data were collected daily by NIMA at their sites. NIMA also supplied weather data, based on yearly averages, for the Air Force sites. The plate motion model used was the NUVEL NNR-1. This model was used in the development of the original GPS-realized WGS 84 station coordinates (Reference 4). Correcting the data using the NUVEL NNR-1 model allowed direct comparison of the original GPS-realized station coordinates and the new coordinates developed in this study. The model currently recommended by the International Earth Rotation Service (IERS), the NNR-NUVEL1A, was used in this study to propagate the new coordinates from the 1994.0 epoch to the 1997.0 epoch.

TABLE 2. GPS BODY-FIXED ANTENNA OFFSETS
(M)

Satellite Type	x	y	z
Block II & IIA	.2794	0.	.9519

HOLLOMAN AFB AND IGS DATA

The data from Holloman AFB and the 19 IGS sites consisted of 30-sec pseudorange and carrier phase data. Data were collected at the Holloman site using an Ashtech ZY-12 receiver. Table 3 lists the IGS stations used, including the site name, 4-character abbreviation, NASA's Crustal Dynamics Project (CDP) number (800X sites are not part of the CDP), type of clock used, and type of receiver.

TABLE 3. IGS ROGUE RECEIVER SITE INFORMATION

Site Name	Abbreviation	CDP Number	Clock	Receiver
Tromso	TROM	7602	Rb	Rogue
Madrid	MADR	1565	H	Rogue
Kootwijk	KOSG	8833	Rb	Rogue
Wettzell	WETT	7224	H	Rogue
Hartebeesthoek	HART	7232	Rb	Rogue
Algonquin	ALGO	7282	H	TurboRogue
Yellowknife	YELL	7285	H	TurboRogue
Goldstone	GOLD	7288	H	Rogue
Fairbanks	FAIR	7225	H	Rogue
Santiago	SANT	1404	H	Rogue
Tidbinbilla	TIDB	1545	H	Rogue
Yarragadee	YAR1	7090	Cs	Rogue
Richmond	RCM5	8009	Cs	TurboRogue
Fortaleza	FORT	8010	H	TurboRogue
Maspalomas	MAS1	8007	Cs	TurboRogue
Pamatai	PAMA	8008	Rb	Rogue
Usuda	USUD	7246	Cs	TurboRogue
Taipei	TAIW	8005	Rb	Rogue
McMurdo	MCM4	8003	I	Turbo Rogue

H is hydrogen maser; Cs is cesium; Rb is rubidium; I is internal , Quartz assumed.

Only about six days of data from Holloman AFB were used. Two days, day numbers 339 and 344, were not available from NIMA. Beginning about midday on day 346 the receiver's frequency standard became unstable, so data from then to the end of the 10 day span were unusable. Some days of data were missing for three IGS sites. Fortaleza was missing data for day 341, Tromso was missing data for days 344 and 345, and Maspalomas was missing data for day 347.

The starting coordinates for Holloman AFB were generated by NIMA using their point positioning program and 3 days of GPS tracking data. The point position solution is for the site's phase center location. The estimates of the IERS Terrestrial Reference Frame 1994 (ITRF94) coordinates for all IGS sites were obtained from IERS Technical Note 20 (Reference 6). The ITRF94 station coordinates for the IGS sites were propagated to the epoch of the data span using their associated velocity, except for McMurdo. An ITRF94 velocity was not available for McMurdo so its coordinates were propagated using the NNR-NUVEL1A geophysical model. Given in Table 4 are the Earth-fixed Cartesian coordinates for Holloman AFB in the WGS 84 and the IGS sites in the ITRF94 at the epoch of the data span, 1995.93. Also presented in Table 4 are the adjustments for antenna height and phase center location for the IGS coordinates. The antenna heights were obtained

TABLE 4. HOLLOMAN AFB AND IGS SITES' COORDINATES EPOCH 1995.93, ANTENNA HEIGHTS AND PHASE CENTER LOCATIONS (M)

Site Name	x	y	z	Antenna Ht.	Phase Ctr
Holloman AFB	-1487367.120	-5151844.040	3444225.320	-	-
Tromso*	2102940.363	721569.383	5958192.094	2.473	0.050
Madrid*	4849202.486	-360329.135	4114913.081	0.000	0.050
Kootwijk*	3899225.272	396731.803	5015078.328	0.105	0.050
Wettzell*	4075578.608	931852.669	4801570.018	0.000	0.050
Hartebeesthoek*	5084625.450	2670366.589	-2768493.954	9.754	0.050
Algonquin*	918129.530	-4346071.244	4561977.821	0.100	0.082
Yellowknife*	-1224452.465	-2689216.109	5633638.281	0.100	0.082
Goldstone*	-2353614.145	-4641385.414	3676976.461	0.000	0.050
Fairbanks*	-2281621.406	-1453595.793	5756961.935	0.116	0.050
Santiago*	1769693.324	-5044574.133	3468321.069	0.093	0.050
Tidbinbilla*	-4460996.092	2682557.084	-3674443.751	0.092	0.050
Yarragadee*	-2389025.487	5043316.880	-3078530.780	0.073	0.050
Richmond	961334.777	-5674074.163	2740535.142	0.000	0.082
Fortaleza	4985386.654	-3954998.588	-428426.517	0.643	0.082
Maspalomas	5439192.263	-1522055.657	2953454.692	0.033	0.082
Pamatai	-5245195.271	-3080472.239	-1912825.404	8.410	0.050
Usuda	-3855262.987	3427432.520	3741020.381	-0.035	0.082
Taipei	-3024781.933	4928936.842	2681234.507	1.768	0.050
McMurdo	-1311703.262	310815.136	-6213255.032	0.183	0.082

*IGS fiducial station

from the Internet site of the Central Bureau of the IGS. The phase center location adjustment, H_{LC}, computed using Equation (1), combines the L1 and L2 phase centers for the antenna type associated with the receiver specified in Table 4.

$$H_{LC} = H_{L1} + \frac{f_2^2}{f_1^2 - f_2^2} (H_{L1} - H_{L2}) \tag{1}$$

where f_1 is the frequency for the L1 carrier, 1575.42 MHZ

f_2 is the frequency for the L2 carrier, 1227.60 MHZ

H_{L1} is the vertical distance from the antenna reference point (ARP) to the L1 phase center

H_{L2} is the vertical distance from the ARP to the L2 phase center

The SA effect was removed from both the pseudorange and the carrier phase observations collected at Holloman AFB and the 19 IGS stations. The carrier phase data were used to smooth the pseudorange data to even 15-min intervals. The carrier phase data were sampled at 15-min intervals and used to form range differences. Holloman AFB and five of the IGS sites (Tromso, Kootwijk, Hartebeesthoek, Fairbanks, and Maspalomas) had receiver clock time offsets large enough to affect the accuracy of their data. For this reason the time tags of the observations were corrected by the receiver's clock time offset.

The receiver at Holloman AFB has the capability to track the AS-encrypted pseudoranges, however, the Rogue and TurboRogue receivers deployed at the IGS stations do not. Pseudorange data collected by Rogue receivers from satellites in AS mode are biased with respect to data from AS-free satellites. The biases can be up to 30 m and are satellite dependent. Because of the magnitude of the biases and their variability, pseudorange data collected by Rogue receivers were not used in this study. Because PRN28 was not broadcasting in AS mode its pseudorange observations collected by Rogue receivers were useable. Biases are also present in the pseudoranges collected with the TurboRogue receivers. The TurboRogue receiver biases, however, are much smaller (about 1 meter) so their pseudorange data were used. Twelve of the 19 IGS stations used Rogue receivers while the other seven used TurboRogue receivers. Carrier phase measurements collected from satellites in AS mode by Rogue and TurboRogue receivers are unbiased.

Using the OMNIS system of programs, observations were corrected and edited. The data were corrected for transmission time effects, GPS antenna offset effects, solid Earth tide effects on station coordinates, relativity effects, and tropospheric refraction effects. The epoch of the station coordinates used was the first day of the data span, so no plate motion correction was needed. Weather data for Holloman and the IGS stations were supplied by NIMA. These data consisted of 20-year mean values for the month of December of temperature, atmospheric pressure, and humidity obtained from the Scott Air Force Base Environmental Technical Applications Center.

REFERENCE TRAJECTORIES

The reference trajectories were integrated using the current NIMA geocentric gravitational constant, GM, value of 398600.4418 km^3/sec^2 along with the JGM-3 gravity field truncated to twelfth degree and order. The nonzero values of coefficients C_{21} ($-.17 \times 10^{-09}$) and S_{21} (1.19×10^{-09}) were the IERS-recommended values (Reference 7). These are added to the geopotential model so that the mean figure axis corresponds with the mean pole position of the IERS Terrestrial Reference Frame. A solid Earth tidal potential model was used with Love's number equal to 0.3. Ocean tidal potential effects were ignored. The Rockwell International radiation pressure model, ROCK42, for Block II/IIA satellites was used. Satellite masses used in the radiation pressure model are given in Table 5. A 5-min integration step was used. A 10-second reduced step size was used during the sun-shadow transition for those satellites in eclipse. The ephemerides were written at a 15-min interval. The Earth orientation values used were final IERS values reported in the IERS Bulletin B.

TABLE 5. SATELLITE MASSES

Satellite Type	Mass (kg)
Block II	890.0
Block IIA	973.0

ORBIT, CLOCK, AND STATION COORDINATE ESTIMATION

To derive and initially evaluate the station coordinates, the 10 days of data collected in December 1995 were used (data set 1 in Table 1). Four different fits were made using either range difference data only or both pseudorange and range difference data. Clock, orbit, and station coordinate estimates were made simultaneously in all cases. Ten one-day fits were done to derive the coordinates. Using the same data set and a subset of it, evaluations of the new coordinates were made.

A 10-deg minimum elevation angle cutoff for observations was used in all fits, except where noted. The NIMA site at USNO was designated the master station for clock estimation. The parameters of solution included satellite and station clocks, orbital elements, radiation pressure scale

and y-axis accelerations, tropospheric refraction error, tracking station coordinates, and Earth orientation. The double differencing method was used. When used, the OCS/NIMA pseudorange data were assigned a minimum sigma of 45 cm while the IGS pseudorange data were assigned a minimum sigma of 100 cm. The range difference data were assigned a minimum sigma of 2 cm. The model used for estimating the tropospheric refraction error was a random walk. Station coordinate corrections were estimated in the east, north, and vertical local reference frame. Corrections for all three components were estimated for all stations except for the 12 IGS fiducial stations. The corrections for fiducial stations' coordinates were constrained to zero (i.e., no corrections were made to the coordinates of the IGS fiducial sites). The *a priori* statistics assumed for all parameters are presented in Table 6.

TABLE 6. *A PRIORI* STATISTICS ON ESTIMATED PARAMETERS

Orbit			
a priori sigmas	radial	along-track	cross-track
position (km)	.01	.03	.03
velocity (km/sec)	$2.x10^{-06}$	$6.x10^{-06}$	$6.x10^{-06}$
Radiation Pressure Scale			
a priori and steady-state sigmas	.1 (unitless)		
decorrelation time	4 hr		
Y-Axis Acceleration			
a priori and steady-state sigmas	$1.x\ 10^{-12}$ km/sec^2		
decorrelation time	4 hr		
Clocks			
a priori sigmas	time offset (nsec)	frequency offset (parts in 10^{12})	frequency drift (parts in 10^{12}/day)
Satellites	1000.	1000.	0
Stations (except master)	1000.	1000.	-
White noise spectral densities	μsec^2/sec	ppm^2/sec	(ppm/sec)^2/sec
Satellites	$0.1111x10^{-02}$	$0.1111x10^{-08}$	0
Stations (except master)	$0.1111x10^{-02}$	$0.1111x10^{-08}$	-
Tropospheric Refraction			
a priori sigma	50 cm		
Random walk variance rate	1.44 cm^2/hr		

TABLE 6. *A PRIORI* STATISTICS ON ESTIMATED PARAMETERS (CONTINUED)

Station Coordinates*			
a *priori* sigmas	east	north	vertical
	1.5 m	1.5 m	1.5 m

Earth Orientation	
	a priori sigma
x and y	50 cm
x and y rate	5 cm/day
UT1-UTC rate	1 msec/day
UT1-UTC acceleration	1 msec/day^2

*No corrections were made to the coordinates of the 12 IGS fiducial sites.

Four cases were examined during the derivation of the new station coordinates. The first case, designated A, used only range difference data. Case B used both pseudorange and range difference data. Case C used both data types, but used a 20 deg elevation cutoff for pseudorange data collected at Colorado Springs. Initially, only data collected at lower elevations, less than 20 deg, at that site were suspected of including large multipath effects. Case D used both data types but no pseudorange data from Colorado Springs and all data for the IGS site at Hartebeesthoek were excluded. In the final analysis, multipath effects were suspected of corrupting pseudorange data collected from Colorado Springs' at some elevations greater than 20 deg. Because it could not be readily determined at what elevation its pseudorange data became free of multipath effects, all pseudorange data from Colorado Springs were deleted. Based on the analysis of results described below, all the data collected at Hartebeesthoek was suspected of being corrupted and not usable for deriving high accuracy station coordinates (see section STATION COORDINATE EVALUATIONS USING FIRST DATA SET). Table 7 summarizes the differences between the four cases.

TABLE 7. FOUR ESTIMATION CASES

Case	Data types	Notes
A	Range difference	10 deg elevation cutoff for all data.
B	Pseudorange & Range difference	10 deg elevation cutoff for all data.
C	Pseudorange & Range difference	20 deg elevation cutoff for Colorado Springs pseudorange data; 10 deg elevation cutoff for all other data.
D	Pseudorange & Range difference	No pseudorange data from Colorado Springs; no pseudorange or range difference data from Hartebeesthoek; 10 deg elevation cutoff for all other data.

Comparison of the resulting orbit estimates and IGS final combined estimates were made for each case. For each one-day fit, Earth-fixed position differences were computed and then transformed to a radial, along-track, and cross-track frame. Root-mean-square (rms) differences were combined over all satellites for each fit span. All the daily rms differences were combined over the 10 fit spans to form overall statistics. Table 8 presents the overall statistics for the four cases. Figure 2 shows the overall rms differences for the four cases. Case D had the smallest rms statistics in all three directions. For this reason, Case D was chosen as the method to derive the new GPS-realized station coordinates.

TABLE 8. ORBIT DIFFERENCES VS. IGS FINAL COMBINED (CM)

	Radial			Along-track			Cross-track		
Case	Mean	Rms	Peak	Mean	Rms	Peak	Mean	Rms	Peak
A	-2	16	131	8	48	273	0	30	136
B	-1	14	123	7	40	287	0	28	143
C	-2	14	123	7	40	291	0	28	143
D	-1	13	120	8	38	321	0	27	126

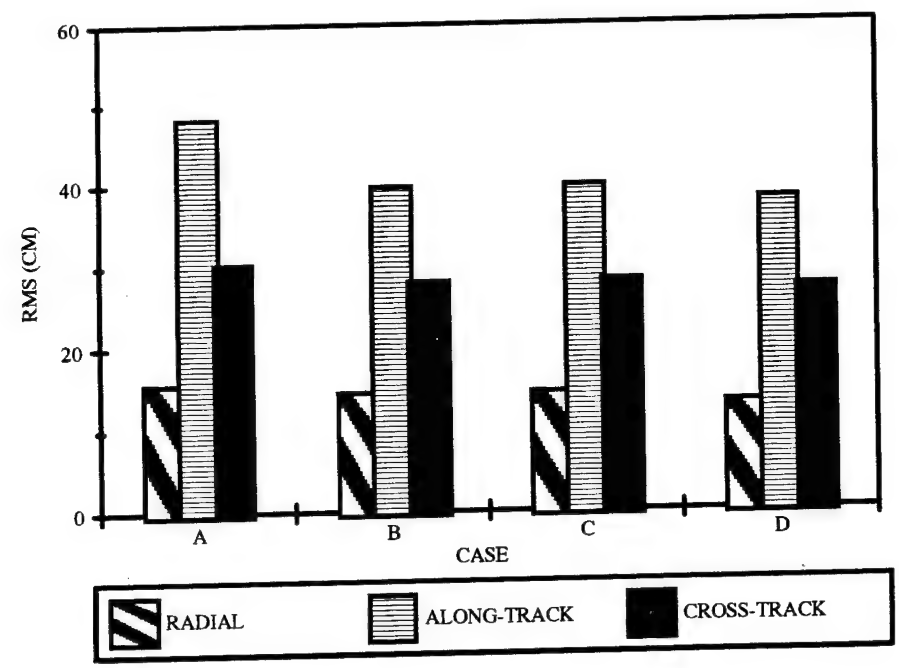

FIGURE 2. ORBIT RMS DIFFERENCES OVER TEN 1-DAY FITS BETWEEN FOUR CASES AND IGS FINAL COMBINED (CM)

Seven-parameter similarity transformations were computed to examine the systematic differences between the orbit estimates of Case D and the IGS final combined estimates. The seven parameters (three translations, scale, and three rotations) were computed over the entire day of the each fit span using each 15-min position from all satellites. After making the least-squares solution, rms differences between transformed and IGS orbits were computed. The transformation parameters reported are the average over the 10 fit spans. The reported rms differences are for all 10 fit spans combined over all satellites.

The transformations were defined such that the seven parameters would transform a set of orbits to be consistent with the IGS orbits. The parameters for the case D orbits are presented in Table 9. The small magnitudes of the transformation parameters indicate the reference frames of the two sets of orbits are fairly consistent. The largest rotations, -1 mas, seen about the y and z axes, equal approximately -13 cm at GPS altitude. The rms differences after the transformation was applied are presented in Table 10. Because the transformation parameters are small, the case D rms differences before transformation (Table 8) and after transformation are similar.

TABLE 9. WGS 84 TO IGS TRANSFORMATION PARAMETERS FOR ORBITS (CASE D)

Translations (cm)			Scale	Rotations (mas)		
x	y	z	parts in 10^8	x	y	z
-1	2	2	0.02	-0.7	-1.0	-1.0

TABLE 10. RMS ORBIT DIFFERENCES AFTER TRANSFORMATION APPLIED (CM)

Case	Radial	Along-track	Cross-track
D	13	36	24

The final set of new WGS 84 coordinates are the average of the estimated station coordinates derived in the 10 one-day fits of case D. The final average adjustments and standard deviations of the coordinates for the five OCS and the seven operational NIMA stations at the 1994.0 epoch are presented in Table 11. The overall means and standard deviations in Table 11 are for the original 10 stations and do not include the statistics from USNO and China. The average adjustments and standard deviations for the 12 OCS/NIMA stations are also presented in Figures 3 and 4, respectively. The east direction corrections for USNO and China are the largest corrections. As mentioned above, USNO and China were not part of the NIMA tracking network when the GPS-realized coordinates were first derived. The starting coordinates of USNO and China were obtained from the NIMA point-positioning procedure. The standard deviations of all 12 stations are small. The square roots of the average variances of the 10 original stations are 1.9, 1.3, and 2.0 cm in the east, north, and vertical directions, respectively. These statistics indicate the 10 one-day solutions are self-consistent. The rms adjustments of the 10 original stations are 4.2, 4.5, and 5.9 cm in the east, north, and vertical directions, respectively. These rms adjustments indicate the claim of 10 cm per component, one sigma, accuracy of the starting coordinates was conservative (Reference 4). The formal uncertainties

TABLE 11. STATION COORDINATE ADJUSTMENTS AT 1994.0 EPOCH BASED ON AVERAGING DAILY ESTIMATES (CM)

Station	East		North		Vertical	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Colo. Springs	0.1	1.1	1.3	0.6	3.3	2.3
Ascension	2.0	2.3	4.0	1.2	-1.1	2.9
Diego Garcia	-3.3	3.1	-8.5	2.0	5.2	3.4
Kwajalein	4.7	2.9	0.3	1.7	4.1	1.6
Hawaii	0.6	1.5	2.6	2.0	2.7	1.9
Australia	-6.2	1.6	-2.7	0.8	7.5	1.1
Argentina	-1.0	1.6	4.1	0.8	6.7	0.8
England	8.8	0.5	7.1	0.6	1.1	1.0
Bahrain	-4.3	1.8	-4.8	1.2	-8.1	2.4
Ecuador	-2.0	1.0	2.5	0.8	10.7	1.0
USNO	39.1	1.4	7.8	0.6	-3.7	1.2
China	31.0	2.7	-8.1	2.2	-1.5	2.4
Mean*	-0.1	4.6	0.6	4.6	3.2	5.3
S.D.*	4.2		4.4		4.9	

* Mean and Standard Deviation do not include statistics for USNO and China.

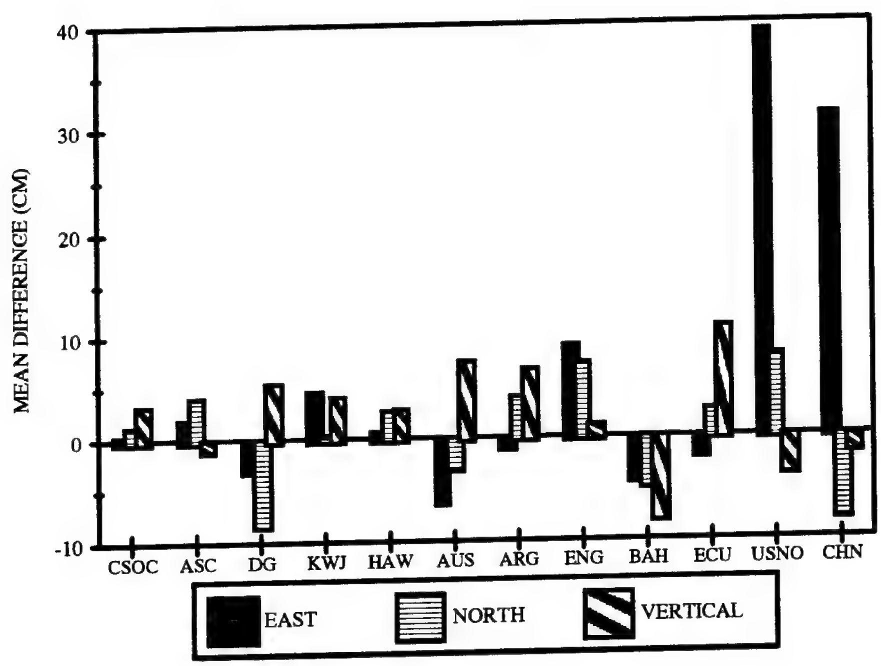

FIGURE 3. CASE D STATION COORDINATE ADJUSTMENTS FOR THE OCS/NIMA SITES (CM)

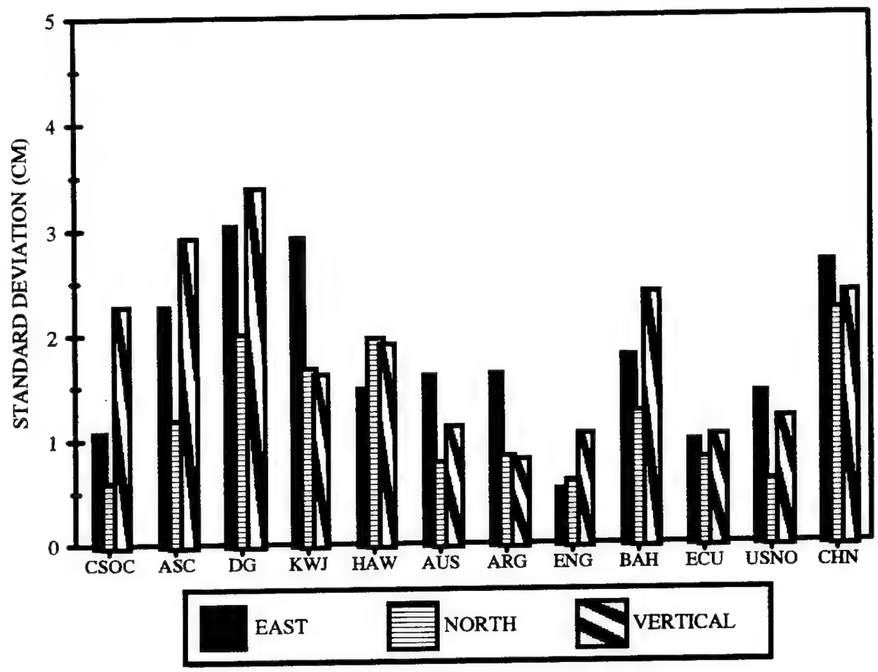

FIGURE 4. CASE D STATION COORDINATE SIGMAS FOR THE OCS/NIMA SITES (CM)

of estimation were generally 3, 1, and 3 cm in the east, north, and vertical directions, respectively.

The coordinate adjustments for cases A, B, and C were examined also. The adjustments for cases A and D were similar. The major differences between the adjustments for cases A and D and those for cases B and C were in the vertical adjustment of Colorado Springs. The vertical adjustments for Colorado Springs were 9.4 cm for case B and 6.9 cm for case C compared to 3.4 cm for case A and 3.3 cm for case D. For the other 11 OCS/NIMA stations, the adjustments generated using range difference data only (case A) were consistent with those generated using both data types (cases B and C). Because Colorado Springs' vertical adjustment exhibited large variability between case A and cases B and C, much of the pseudorange data from that site was suspected of being corrupted by multipath noise. The elevation where Colorado Spring's pseudoranges became free of multipath effects was unknown, so all the pseudoranges from that site were considered not usable for deriving high accuracy coordinates.

The new WGS 84 coordinates at the 1997.0 epoch were generated by applying the plate motion corrections based on the IERS recommended (Reference 8) NNR-NUVEL1A model to the Cartesian coordinates derived in case D. The propagated coordinates were then converted to geodetic coordinates. Reported in Table 12 for the 12 operational stations are the plate motion corrections over the three year period and NIMA's current station numbers. The plate motion correction over approximately one year for Holloman AFB and the plate name for each station are also reported. The means and standard deviations reported in Table 12 do not include the plate motion for Holloman AFB. The corrections are reported by east and north components as well as by magnitude and

azimuth. The GPS-realized WGS 84 coordinates for epoch 1994.0 are reported in Table 13 and those for epoch 1997.0 are reported in Table 14. The coordinates for USNO in Tables 13 and 14 include an antenna height change (+3.013 m) effective 27 August 1996.

To expose any systematic differences between the starting coordinates and the new coordinates, a seven-parameter similarity transformation (three translations, scale, and three rotations) was estimated using 10 of the 12 OCS/NIMA stations. USNO and China were excluded from the transformation estimation because they were not in operation when the first set of GPS-realized coordinates were generated. The least-squares solution for the transformation's seven parameters, computed using the positions of the 10 stations, is reported in Table 15. The largest rotation, -1.47 mas, seen about the x-axis corresponds to about -5 cm at the Earth's surface. Reported in Table 16 are two sets of rms differences over all 10 stations. The first set is the rms differences between the new coordinates and the starting coordinates. The second set is the rms differences between the new coordinates and the starting coordinates transformed using the seven-parameter transformation defined in Table 15. All seven transformation parameters and both sets of differences are small. The consistency between the starting and new coordinates demonstrated by these results indicate that the accuracy estimate of 10 cm per component for the starting coordinates was conservative (Reference 4).

TABLE 12. PLATE MOTION FROM 1994.0 TO 1997.0 (CM)

Station	NIMA Station Number	East	North	Mag	Azimuth (deg)	Plate Name
Colo. Springs	85128	-4.3	-2.2	4.8	242.9	North America
Ascension	85129	-1.8	3.3	3.8	331.2	South America
Diego Garcia	85130	13.7	11.3	17.7	50.4	Australia
Kwajalein	85131	-19.6	8.4	21.3	293.3	Pacific
Hawaii	85132	-17.5	9.7	20.0	299.0	Pacific
Australia	85402	7.2	17.3	18.7	22.6	Australia
Argentina	85403	-0.6	3.2	3.3	350.0	South America
England	85404	5.1	4.6	6.9	48.0	Eurasia
Bahrain	85405	8.4	10.5	13.4	38.6	Arabia
Ecuador	85406	-1.7	2.5	3.0	326.7	South America
USNO	85407	-4.5	1.1	4.6	283.3	North America
China	85409	6.7	-3.7	7.7	118.7	Eurasia
Holloman AFB*	-	-1.2	-0.8	1.5	237.5	North America
Mean**		-0.7	5.5	10.4		
S.D.**		9.6	6.8	6.9		

* Plate motion from 1995.93 to 1997.0

** Mean and Standard Deviation do not include plate motion for Holloman AFB.

TABLE 13. GPS-REALIZED WGS 84 COORDINATES AT THE 1994.0 EPOCH

Station	E. Longitude	Latitude	Height	x	y	z
	(deg)	(deg)	(m)	(m)	(m)	(m)
Colo. Springs	255.47540979	38.80305495	1911.757	-1248597.176	-4819433.244	3976500.210
Ascension	345.58787010	-7.95133078	106.654	6118524.214	-1572350.810	-876464.122
Diego Garcia	72.36311970	-7.26655100	-63.667	1917032.316	6029782.294	-801376.225
Kwajalein	167.73053088	8.72249897	40.038	-6160884.615	1339851.497	960842.894
Hawaii	201.76067346	21.56148911	428.234	-5511982.250	-2200248.271	2329481.564
Australia	138.64734303	-34.72900411	38.183	-3939181.855	3467075.372	-3613221.177
Argentina	301.48070114	-34.57370269	48.781	2745499.089	-4483636.535	-3599054.694
England	358.71610734	51.45374165	163.113	3981776.753	-89239.205	4965284.579
Bahrain	50.60814234	26.20913798	-13.853	3633911.005	4425277.688	2799862.583
Ecuador	281.50639148	-0.21515850	2922.667	1272867.294	-6252772.263	-23801.915
USNO	282.93377657	38.92045005	59.168	1112168.486	-4842861.710	3985487.195
China	115.89248174	39.60860230	87.642	-2148743.843	4426641.473	4044656.129
Holloman AFB*	253.89627000	32.88821828	1234.634	-1487366.802	-5151844.353	3444225.488

*Plate motion epoch 1995.93

TABLE 14. GPS-REALIZED WGS 84 COORDINATES AT THE 1997.0 EPOCH

Station	E. Longitude	Latitude	Height	x	y	z
	(deg)	(deg)	(m)	(m)	(m)	(m)
Colo. Springs	255.47540928	38.80305475	1911.757	-1248597.221	-4819433.246	3976500.193
Ascension	345.58786992	-7.95133048	106.654	6118524.214	-1572350.829	-876464.089
Diego Garcia	72.36312094	-7.26654999	-63.667	1917032.190	6029782.349	-801376.113
Kwajalein	167.73052910	8.72249973	40.038	-6160884.561	1339851.686	960842.977
Hawaii	201.76067177	21.56148998	428.234	-5511982.282	-2200248.096	2329481.654
Australia	138.64734382	-34.72900255	38.183	-3939181.976	3467075.383	-3613221.035
Argentina	301.48070108	-34.57370240	48.781	2745499.094	-4483636.553	-3599054.668
England	358.71610807	51.45374207	163.113	3981776.718	-89239.153	4965284.609
Bahrain	50.60814318	26.20913892	-13.853	3633910.911	4425277.706	2799862.677
Ecuador	281.50639133	-0.21515827	2922.667	1272867.278	-6252772.267	-23801.890
USNO	282.93377605	38.92045014	59.168	1112168.441	-4842861.714	3985487.203
China	115.89248252	39.60860198	87.642	-2148743.914	4426641.465	4044656.101
Holloman AFB	253.89626986	32.88821821	1234.634	-1487366.815	-5151844.354	3444225.481

TABLE 15. STARTING WGS 84 TO NEW WGS 84 TRANSFORMATION PARAMETERS

x translation	-0.3	cm
y translation	-1.2	cm
z translation	-1.1	cm
scale	0.51	parts in 10^8
rotation about x	-1.47	mas
rotation about y	-0.38	mas
rotation about z	-0.07	mas

TABLE 16. RMS DIFFERENCES OVER 10 STATIONS BETWEEN
STARTING WGS 84 VS. NEW WGS 84 COORDINATES
AND
TRANSFORMED STARTING VS. NEW WGS 84 COORDINATES (CM)

	Starting vs. New	Transformed Starting vs. New
East	4.2	4.4
North	4.5	3.0
Vertical	5.9	4.4

The final average adjustments and standard deviations of the Holloman AFB station and the seven non-fiducial IGS station coordinates at the 1995.93 epoch are given in Table 17. Also presented in Table 17 are the IERS station classifications related to the quality of the station coordinates. The mean and standard deviations reported in Table 17 do not include the statistics from Holloman AFB, Maspalomas, and Pamatai. The IERS distinguishes four classes: A, B, C and Z. Class A coordinates agree to better than 2 cm when derived by at least two independent techniques. Class B coordinates agree to better than 3 cm; class C have larger deviations but no large residuals. Class Z coordinates have larger residuals (Reference 6).

The east direction correction for Holloman AFB (Table 17) is about as large and in the same direction as the east corrections for USNO and China reported in Table 11. The starting coordinates of Holloman AFB were also obtained from the NIMA point-positioning procedure. The corrections for Maspalomas and Pamatai show the largest vertical corrections of all the IGS stations. Both sites had about half as many observations as the other IGS sites. The large corrections and standard deviations indicate the data from these sites may have been corrupted. The other five IGS stations show smaller corrections with smaller standard deviations. The small standard deviations of these five IGS stations indicate that their 10 solutions are self-consistent. The statistics for these five IGS stations are evidence of the overall good accuracy of both the OCS/NIMA and IGS derived coordinates.

TABLE 17. HOLLOMAN AFB AND IGS STATION COORDINATE ADJUSTMENTS AT 1995.93 EPOCH BASED ON AVERAGING DAILY ESTIMATES (CM)

Station	East		North		Vertical		
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Class
Holloman AFB	39.2	1.5	2.5	1.0	27.0	1.2	-
Richmond	-1.4	0.8	-1.3	0.8	2.6	2.2	A
Fortaleza	-4.2	2.2	-1.6	1.1	6.6	2.4	B
Maspalomas	5.0	10.4	5.4	14.4	32.7	40.8	C
Pamatai	14.8	16.4	1.3	4.3	30.1	29.7	C
Usuda	3.5	3.4	-1.7	1.4	2.0	2.6	C
Taipei	3.9	3.7	-3.6	1.4	1.3	5.1	C
McMurdo	-0.2	1.2	-3.9	0.9	-5.1	2.8	C
Mean*	0.3	4.0	-2.4	1.6	1.5	4.9	
S.D. *	3.1		1.1		3.8		

* Mean and Standard Deviation do not include statistics for Holloman AFB, Maspalomas, and Pamatai.

Six Earth orientation parameters were estimated in each orbit fit. As mentioned above, the IERS final values found in Bulletin B were used as the Earth orientation starting values. Polar motion estimates for the beginning and end of each one-day fit span were differenced with the IERS final values. Because just the rate and acceleration of UT1-UTC were estimated, only the estimates of UT1-UTC from the end of each one-day fit were differenced with the IERS final values. The statistics presented in Table 18 are the average differences and the standard deviations over the 10 fit spans for the case D estimates. The small mean differences in x and y indicate the reference frame defined by the 11 IGS fiducial sites is fairly consistent with the IERS pole.

TABLE 18. EARTH ORIENTATION DIFFERENCES VS. IERS FINAL VALUES

x (mas)		y (mas)		UT1-UTC (msec)	
Mean	S.D.	Mean	S.D.	Mean	S.D.
0.9	0.7	0.9	0.6	-0.15	0.05

STATION COORDINATE EVALUATIONS USING FIRST DATA SET

Using the first data set (i.e., the 10 days of data used to derive the new station coordinates, see Table 1) two different tests were made to evaluate the new OCS/NIMA station coordinates. The first involved comparing GPS clock and orbit estimates generated using the new coordinates with estimates generated using the starting coordinates. The second test involved holding the new OCS/NIMA station coordinates fixed and solving for all the IGS station coordinates.

Clock and orbit estimates generated using the new WGS 84 coordinates were compared with estimates generated using the coordinates NIMA uses in their production. The NIMA production coordinates are this study's starting coordinates discussed above. The starting coordinates will also be referred to as the "old" WGS 84 coordinates. Clock and orbit estimates generated using the old coordinates will be referred to as the "old" estimates. Likewise, the "new" estimates were generated using the new WGS 84 coordinates derived in this study. Eight three-day fits were made over the same days used to generate the new WGS 84 coordinates, however, for this evaluation only data from the 12 OCS/NIMA production stations were used. The technique of estimation used with both sets of coordinates was similar to the production technique that NIMA started using in October, 1996. The parameters of solution included satellite and station clocks, orbital elements, radiation pressure and y-axis accelerations, tropospheric refraction error, and Earth orientation. Both the production and the new station coordinates were held fixed. The double differencing method was used. The OCS/NIMA pseudorange data were assigned a minimum sigma of 45 cm. The range difference data were assigned a minimum sigma of 2 cm. The model used for estimating the tropospheric refraction error was a random walk.

Clock and orbit comparisons for all 24 satellites were made between the two sets of estimates. For each three-day fit span, Earth-fixed position differences were computed for the middle day of each fit span and then transformed to a radial, along-track, and cross-track frame. Clock differences, also computed for the middle day of each fit span, were converted from nanoseconds to meters. Rms differences were combined over all satellites for each fit span. All the daily rms differences were combined over the eight fit spans to form overall statistics. The overall statistics are reported in Table 19. The along-track component shows an overall mean difference of 27 cm. The rms overall statistics are 35 cm in the along-track direction and 30 cm in the cross-track direction.

TABLE 19. CLOCK AND ORBIT DIFFERENCES - NEW WGS 84 VS. OLD WGS 84 (CM)

Clock				Radial			Along-track			Cross-track		
	Mean	Rms	Peak	Mean	Rms	Peak	Mean	Rms	Peak	Mean	Rms	Peak
ALL	2	8	49	0	4	16	27	35	59	0	30	75

Orbit comparisons were also made between the estimates generated using both the old coordinates and the new WGS 84 coordinates and the IGS final combined estimates. The radial, along-track, and cross-track overall differences for the middle day of the fits for both the old and new orbits are reported in Table 20. Presented in Figure 5 are the overall rms differences for the old and new orbits. Using the old coordinates the overall mean in the along-track direction is −22 cm. A smaller overall mean of 5 cm is present in the along-track direction of the new estimates. The rms differences in both the along-track and cross-track directions are also larger for the old estimates. Orbit User Range Error (URE) statistics were also computed for each fit span using the IGS estimates as "truth". The URE is a function of the satellite orbit and clock errors. Generally, URE is the error a user would incur in measured range due, predominately, to satellite orbit and clock errors and to a lesser extent other sources. Because IGS provides only orbit estimates, the URE statistics presented have no clock error contribution. The overall rms orbit-URE for the new orbits

is 12 cm. The overall rms orbit-URE for the estimates generated using the old coordinates is 14 cm.

TABLE 20. ORBIT DIFFERENCES VS. IGS FINAL COMBINED (CM)

	Radial			Along-track			Cross-track		
Case	Mean	Rms	Peak	Mean	Rms	Peak	Mean	Rms	Peak
Old	0	10	46	-22	45	165	-1	34	140
New	1	10	51	5	37	125	-1	24	80

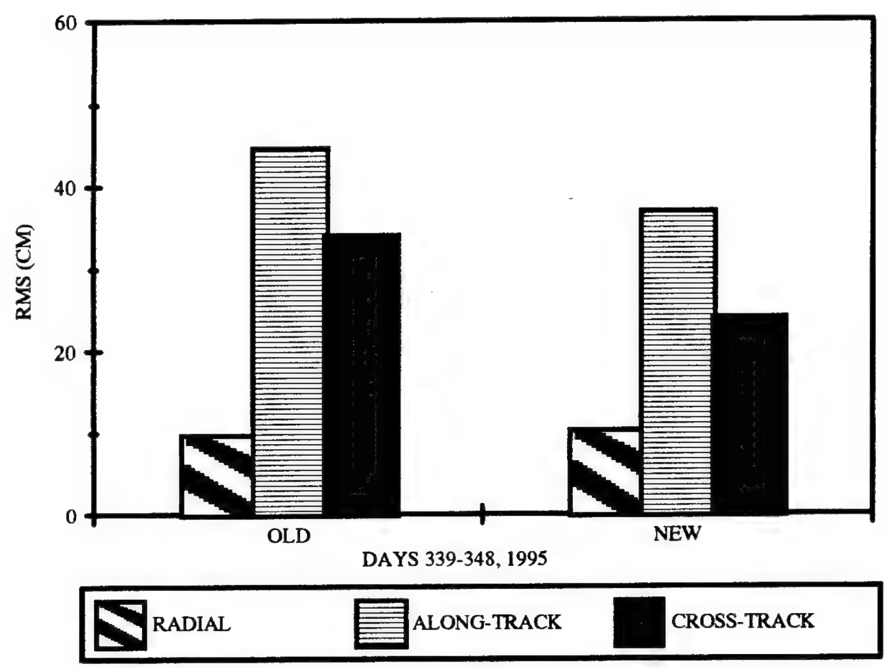

FIGURE 5. OLD AND NEW ORBIT DIFFERENCES VS.
IGS FINAL COMBINED OVER ALL EIGHT 3-DAY FITS (CM)

Reported in Table 21 are the seven parameters describing the similarity transformation between orbits generated using the old and new coordinates and the IGS final combined orbits. All the transformation parameters are small for both the old and new cases. The rotations corresponding to the estimates generated using the old coordinates are the largest parameters. The rotation about the x-axis, -2.5 mas, corresponds to about -32 cm at the GPS altitude. The rms of the orbit differences after transformation between both the old and new estimates and the IGS final combined orbits are given in Table 22. Both sets of rms differences are nearly identical to the rms differences for the new coordinates before transformation given in Table 20. These results show that using the new station coordinates reduces the small systematic differences which exist in the old sets of orbits.

TABLE 21. TRANSFORMATION PARAMETERS FROM OLD AND NEW TO IGS FINAL COMBINED ORBITS

Comparison	Old vs. IGS	New vs. IGS	Units
Parameter			
x translation	2	-1	cm
y translation	-2	1	cm
z translation	1	2	cm
scale	-0.02	-0.03	parts in 10^8
rotation about x	-2.5	-0.6	mas
rotation about y	-1.9	-1.2	mas
rotation about z	2.5	-0.7	mas

TABLE 22. RMS ORBIT DIFFERENCES OF OLD AND NEW VS. IGS FINAL COMBINED ORBITS AFTER TRANSFORMATION APPLIED (CM)

Case	Radial	Along-track	Cross-track
Old	11	38	27
New	10	35	22

The Earth orientation differences from IERS final values for the two cases are given in Table 23. The mean differences in x and y corresponding to the new coordinates are smaller than those differences related to the old coordinates. The mean differences related to the new coordinates are about the same as those differences reported in Table 18. These results indicate that the new WGS 84 coordinates also are fairly consistent with the IERS pole.

TABLE 23. EARTH ORIENTATION DIFFERENCES OF OLD AND NEW FROM IERS

	x (mas)		y (mas)		UT1-UTC (msec)	
Case	Mean	S.D.	Mean	S.D.	Mean	S.D.
Old	1.2	0.2	2.8	0.3	-0.08	0.04
New	0.8	0.2	0.7	0.3	-0.10	0.04

The second evaluation using the first data set involved holding fixed the new coordinates for the 12 operational OCS/NIMA stations and solving for the coordinates of the 18 IGS sites used in case D. Eleven of the sites are fiducial sites and were held fixed in the case D fits. Ten one-day fits were made using a technique similar to that described for Case D. Presented in Table 24 are the mean

adjustments of the station coordinates estimated for the 11 IGS fiducial sites. The IERS classification is also reported. (The IERS classes were discussed above on page 16). Similar analyses were done for cases A, B, and C. When solving for Hartebeesthoek's station coordinates in these cases, large adjustments mostly in the vertical directions (approximately 44 cm) were made to its starting position. For this reason Hartebeesthoek was not included in the case D fits.

The small mean adjustments presented in Table 24 are further evidence that the reference frame defined by the new WGS 84 OCS/NIMA station coordinates is fairly consistent with the ITRF94. The largest mean adjustments for the 11 IGS stations appear in the vertical direction. For all fiducial stations, the standard deviations are small indicating the 10 solutions are self-consistent.

TABLE 24. MEAN STATION COORDINATE ADJUSTMENTS AND IERS CLASSIFICATION FOR 11 IGS STATIONS (CM)

Station	East		North		Vertical		Class
	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Tromso	-0.3	1.3	0.5	0.8	4.5	2.7	B
Madrid	0.2	0.9	0.5	0.5	-1.7	1.7	A
Kootwijk	-0.2	1.3	0.1	1.1	4.1	1.4	A
Wettzell	1.0	1.2	0.7	0.6	1.8	2.9	A
Algonquin	1.0	1.8	0.0	1.0	3.0	1.3	B
Yellowknife	-2.1	0.9	-0.1	0.8	4.7	1.8	B
Goldstone	-2.5	1.6	0.4	0.8	6.6	2.2	C
Fairbanks	1.1	1.6	-0.6	1.0	6.1	1.5	B
Santiago	0.6	1.5	-2.3	0.5	1.8	1.6	B
Tidbinbilla	-1.7	1.8	0.0	0.6	1.8	2.6	B
Yarragadee	-1.7	2.4	-1.8	0.7	6.7	2.8	B
Mean	-0.4	2.0	-0.2	1.2	3.6	3.2	
S.D.	1.3		0.9		2.4		

STATION COORDINATE EVALUATION USING SECOND DATA SET

The new station coordinates were also evaluated using the 1996 data set (set 2 in Table 1). Clock and orbit estimates were generated for GPS week 857 using both the new and old coordinates. The same fit spans used in the NIMA production fits were used in this evaluation. Four three-day fits were used to generate estimates for the first four days of the week. A five-day fit span was used to generate estimates for the last three days of the week. The reference orbits used in this evaluation were the ones used by NIMA in their production fits. Data from the 12 OCS/NIMA production stations were used. The parameters of solution were the same as those used by NIMA in their production fits: satellite and station clocks, orbital elements, radiation pressure scale and y-axis

accelerations, tropospheric refraction error, and Earth orientation. Station coordinates were held fixed. The double differencing method was used. The OCS/NIMA pseudorange data were assigned a minimum sigma of 45 cm. The range difference data were assigned a minimum sigma of 2 cm. A Gauss-Markov process was used for estimating the tropospheric refraction.

Orbit comparison were made between the IGS final combined estimates and the estimates generated using both the old and new coordinates. The radial, along-track, and cross-track overall differences for the middle day of the three-day fits and for the middle three days of the five-day fit for both the old and new orbits are reported in Table 25. Presented in Figure 6 are the overall rms differences.

TABLE 25. ORBIT DIFFERENCES VS. IGS FINAL COMBINED (CM)

	Radial			Along-track			Cross-track		
Case	Mean	Rms	Peak	Mean	Rms	Peak	Mean	Rms	Peak
Old	1	11	43	-17	50	158	1	43	138
New	1	10	38	11	40	128	1	28	87

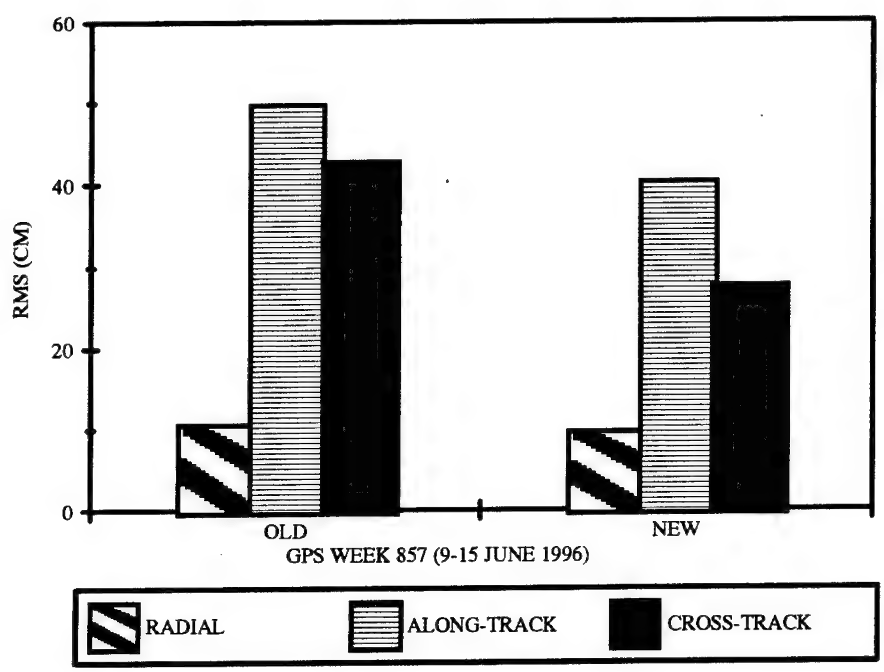

FIGURE 6. OLD AND NEW ORBIT DIFFERENCES VS. IGS FINAL COMBINED FOR GPS WEEK 857 USING NIMA PRODUCTION FITS SPANS (CM)

Differences for PRN26 from the second three-day fit (middle day number 162) were not included in the overall statistics. PRN26 experienced a thrust about mid-day on day 162. The estimates generated using the new coordinates show smaller differences with the IGS estimates, especially in the along-track and cross-track directions. A mean difference in the along-track direction is reduced from −17 cm when using the old coordinates to 11 cm when the new coordinates are used. The overall rms differences in the along-track direction decreased 10 cm when using the new coordinates and the rms differences in cross-track direction decreased 15 cm. Orbit-URE statistics were computed for each fit span using the IGS estimates as "truth". The overall rms orbit-URE for the old orbits is 14 cm and that for the new orbits is 12 cm.

The seven-parameter similarity transformation between orbits generated using the old and new coordinates and the IGS final combined orbits are reported in Table 26. Larger systematic differences are found between the old and IGS orbits than between the new and the IGS orbits. The largest systematic difference occurs in the rotation about the x axis. This difference, −3.3 mas, corresponds to about −42 cm at GPS altitude. The rms of the orbit differences after transformation between both the old and new estimates and the IGS final combined orbits are given in Table 27. The rms differences between the new and IGS orbits are nearly identical to the rms differences for the new orbits before transformation given in Table 25. This confirms that the systematic differences in the new orbits are small.

TABLE 26. TRANSFORMATION PARAMETERS FROM OLD AND NEW TO IGS FINAL COMBINED ORBITS

Comparison	Old vs. IGS	New vs. IGS	Units
Parameter			
x translation	3	0	cm
y translation	−2	2	cm
z translation	1	2	cm
scale	−0.04	−0.05	parts in 10^8
rotation about x	−3.3	−1.4	mas
rotation about y	− 1.8	−0.9	mas
rotation about z	2.1	−1.3	mas

TABLE 27. RMS ORBIT DIFFERENCES OF OLD AND NEW VS. IGS FINAL COMBINED ORBITS AFTER TRANSFORMATION APPLIED (CM)

Case	Radial	Along-track	Cross-track
Old	11	36	31
New	10	36	24

SUMMARY AND CONCLUSIONS

Using 10 days of data collected from 31 stations, estimates of GPS clocks, orbits, and tracking station coordinates were generated. Both pseudorange and range difference data were used in the one-day fits. WGS 84 station coordinates were derived in a reference frame defined by 11 IGS fiducial stations whose ITRF94 coordinates were held fixed during estimation. The WGS 84 coordinates of the seven operations NIMA sites, the five OCS sites, and an additional NIMA site at Holloman AFB are the average of the estimated station coordinates derived in the 10 one-day fits. Using the NNR-NUVEL1A plate motion model, the new coordinates at the 1994.0 epoch were propagated to the 1997.0 epoch.

The starting (also referred to as old) WGS 84 coordinates of 10 of the 12 OCS/NIMA operational stations were derived using GPS data in a previous study. The claim of 10 cm per component, one sigma, accuracy for the coordinates of those sites was conservative based on the results of the current work. Only one site of the 10 showed a mean adjustment in any component of slightly greater than 10 cm. For these 10 stations the rms adjustments were less than 6 cm in all three components. Small systematic differences between the starting and new coordinates also support the claim of less than 10 cm accuracy.

The one sigma accuracy of the WGS 84 coordinates for the 12 OCS/NIMA sites and Holloman AFB derived in this work is estimated to be better than 5 cm per component. This estimate is based on the standard deviations of the adjustments and the corrections made to the IGS fiducial sites during an evaluation procedure. For each of the thirteen OCS/NIMA sites, the standard deviation of the adjustments of each component is better than 5 cm. These statistics show the 10 one-day solutions are self-consistent to this level. Further, an experiment was performed to estimate coordinate adjustments for the 11 IGS fiducial sites while holding the new WGS 84 coordinates fixed. The rms adjustments over all the IGS fiducial sites were 1.4, 1.0, and 4.3 cm in the east, north and vertical directions, respectively.

To further evaluate the new WGS 84 coordinates, GPS clock and orbit estimates were generated employing the data set used to derive the coordinates and an independent data set. Orbit estimates generated using the old and new coordinates were compared to the IGS final combined orbits. The orbit estimates generated using the new WGS 84 coordinates agreed better with the IGS estimates. A significant reduction occurs in the mean along-track difference when the new coordinates are employed. Rms differences in the along-track and cross-track directions are also smaller when the new coordinates are used. The rms overall orbit-URE for the new orbits was 12 cm. Systematic differences between the new orbits and the IERS orbits are also smaller.

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